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STATUS REPORT ON THERMAL-HYDRAULIC PASSIVE SYSTEMS DESIGN AND SAFETY ASSESSMENT

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Abstract

Passive systems noticeably those which are capable of transferring thermal power from a heat source to a sink without the use of energy which is not coming from gravity are in use of nuclear technology since the pioneering design of reactors. They received a step-wise, fashion-type, renewed interest following the three major nuclear accidents in 1979, 1986 and 2011. The words thermal-hydraulic passive systems, design and safety, open to a myriad of research and application activities, which without surprise may appear contradictory and, at least, not converging into a common understanding. In the present paper an attempt is made to use the word reliability in order to select a space in the design and safety assessment and to derive agreeable outcomes for the technology of passive systems. The key conclusions are: (a) passive systems are not the panacea for protecting the core of nuclear reactors in each foreseeable accident condition; (b) specific licensing rules are strictly needed and not yet formulated; (c) reliability of operation, once a target mission is assigned, may reveal not unit; (d) systems implying the use of active components like pumps shall not be avoided in future designed/built nuclear reactors.

1. INTRODUCTION

Passive systems are embedded into the nuclear reactor technology design and safety since the beginning of the 'nuclear' era. In relation to design, the layout of primary systems of both Pressurized Water Reactor (PWR) and Boiling Water Reactors (BWR) is fixed based on natural circulation: the mutual positions of core and steam generators in the case of PWR and the elevation of the feedwater nozzle in the BWR vessel are designed to ensure (at least) removal of decay heat when active systems – noticeably, centrifugal pumps – are not available. In relation to safety, accumulators are one example of vital passive systems strictly needed to mitigate consequences of Large Break Loss of Coolant Accidents (LB-LOCA).

Here it seems worthwhile to note that any safety system, either active or passive, added to an already complex nuclear reactor designed to produce electrical power may introduce triggering causes for accidents and may interact with other existing system during the progression and eventually the mitigation of the accident.

Immediately after the Chernobyl accident in 1986, the passive systems received renowned attention by industry and scientists, noticeably and primarily in those Countries where that event had significant impact upon the exploitation of fission reaction for energy production. In other terms passive systems were taken as a remedy to unforeseeable situations, i.e. capable of mitigating or even avoiding the progression of accidents. The designs of Simplified Boiling Water Reactor (SBWR) and of the Advanced PWR (AP-600 and, more recently, AP-1000) were significant outcomes. The Fukushima accident in 2011 reinforced, in this case in all Countries, the interest towards passive systems, although those systems, ultimately, did not prove their effectiveness during the concerned event.

One may add at this point that the Three Mile Island accident in 1979 shifted the attention of nuclear safety analysists from LB-LOCA to Small Break LOCA (SB-LOCA), i.e. accident scenarios dominated by natural circulation which constitutes a key phenomenon at the basis of the design of (selected) passive systems: definitely, all major nuclear accidents have a connection with passive systems).

All of this may be further synthesized by two statements:

- Passive systems are part of nuclear technology.
- Passive systems are seen as inherently protective systems for the complex (whatever complexity, whatever unexpected situation) nuclear reactors.

The former item testifies, among other things, of a wide technical literature. The latter item (also as a consequence of the former) may be taken as the visible tip of an iceberg of concerns, hopes, design activities and results of research activities connectable with passive systems: namely this is the concern for the present paper.

A universe of findings, situations and opinions actually characterizes passive systems; key-words connectable with related components or operation conditions are: accumulator, battery for powering Pilot operated Relief Valve (PORV), Isolation condenser (IC) Heat Exchanges (HEX), turbine and pump of Reactor Core Isolation Cooling (RCIC), condensation in Pressure Suppression Pool (PSP), natural convection in pools and containment open space, gas (noticeably hydrogen) stratification, natural circulation (NC) during Core Make-up (CMT) draining, Steam Generator (SG) cooling of the core, condensation on containment wall, electrical wire, channel blockage caused by debris, instability in a single boiling channel or in parallel channels, quench front progression during reflood, etc. One may also argue that the recently issued list of 116 thermal-hydraulic phenomena for code validation which are expected to cover Design Basis Accident (DBA) conditions in Water Cooled Nuclear Reactors (WCNR), [1], is entirely applicable to passive systems with the exception of a couple of phenomena dealing with centrifugal pumps and fans.

It is understandable that: (a) any generic statement about passive systems may become questionable or invalid in each of the applicable situations; (b) fields for passive systems research are in number which cannot be easily quantified. Therefore there should be no surprise that a recent effort completed within International Atomic Energy Agency (IAEA) framework, [2], concludes that ‘clear need to obtain more data’ and ‘more practical approach [for the evaluation of reliability of passive systems] would be very helpful’ and a new international project has been planned and just started by the Committee on the Safety of Nuclear Installations (CSNI) of OECD/NEA, [3].

At this point it is clear that one paper may not reasonably cover or even touch all the aspects connected with passive systems. Rather the objective here is to issue a Technical Opinion Paper (TOP) in relation to the reliability of a passive system. To this aim the first step is to isolate a space from the iceberg of knowledge above mentioned. Then insights into the selected topic are summarized which do not necessarily reflect the views and the findings available from international activities, e.g. [2] and [3].

2. SCOPE FOR PROVIDING A TECHNICAL OPINION

Providing a technical opinion in relation to the reliability of passive systems implies considering proper constraints to the scope of the activity. A list of assumptions and constraints to limit the field of investigation (and of application) is given below including motivations.

- The Small Modular Reactors (SMR) are not within the scope although selected derived considerations are applicable. The unknown design features and the complexity of a suitable reliability analysis constitute the main motivation: in other terms, a suitable reliability analysis is expected to provide an answer in relation to acceptability of SMR and that answer cannot be found in the present paper where general concepts are discussed (and no analysis is performed).

- The AP-1000 is not included in the present scope because of the large number of passive systems interacting among each other adding up to the variety of involved components and thermal-hydraulic phenomena. Likewise the case of SMR and other reactors not mentioned here, selected derived considerations from the paper are applicable.

- The reliability of mechanical electrical and electronic components, like valves, pipes and welding unavoidably, Instrumentation and Control (I&C), batteries and wires are not concerned in the TOP: main reason is the access to failure databases and the data analysis not performed here.

- The distinction among classes of passive systems, e.g. from IAEA [4], because of the attention here focusing on thermal-hydraulics, is irrelevant within the present context.

- The NC phenomena occurring in PWR between Reactor Pressure Vessel (RPV) and SG and in BWR inside the RPV between core and down-comer, [5], are not of main interest here, although considered methodological approaches can be utilized in those conditions. The motivation is that wide range investigations are performed and related outcomes appear suitable for design and for assessing the safety of PWR and BWR.

- Instability in boiling channels which are specific of BWR core region, [6], are not of main interest here, although (again) considered methodological approaches can be utilized in those conditions. The motivation is that wide range investigations are performed and related outcomes appear suitable for design and for assessing the safety of BWR.

The scope for the present TOP is restricted to the thermal-hydraulic phenomena expected in the system sketched in Fig. 1, also called the reference system. The system is characterized by an IC-typical configuration and it aims at removing decay power from the core with the heat sink constituted by a pool located a few meters away from the core at an upper elevation. One heat exchanger, a surrounding pool, inlet and outlet pipes and at least one isolation valve to trigger the operation are part of the system; the core with its surrounding RPV is part of the passive system although both the core and the RPV are part of the main reactor cooling system; furthermore, not shown in the figure, other valves may be associated with the operation of the concerned system like isolation valves installed in steam lines when the IC is used to cool the SG or in discharge lines of pressurizer, accumulator or CMT when the PRHR (see below) is used in AP-1000. Single and two-phase NC is expected to occur in a boiling condenser mode when two-phase conditions are present. The system has applications in PWR (noticeably including AP-1000 where the name of the system is Pressurized Residual Heat Removal, PRHR), BWR and SMR where core power constitutes the heat source and SG where the heat source is constituted by the primary side of tubes.

Items above like NC across the core or instability are part of the thermal-hydraulic phenomena expected for the reference system; however, geometries, range of parameters time spans of interest, computational capabilities are not necessarily the same as expected in relation to the reference system.

Key questions to be answered by any reliability study (see next section for the meaning) and specifically considered by the present TOP, except question (2), are:

(1) Is the system better than an equivalent system equipped with (one or more) active components like pumps?
(2) Is the system cheaper than an equivalent active system also in relation to maintenance?
(3) Is the design of the system optimized (i.e. in relation to distance between heat sink and heat source, effective heat transfer area in the heat exchanger, pipe diameter)?

Restricting to such a narrow range the scope of investigation for the TOP allows conclusions which may be more easily understandable and may be useful to form the basis of a common understanding.

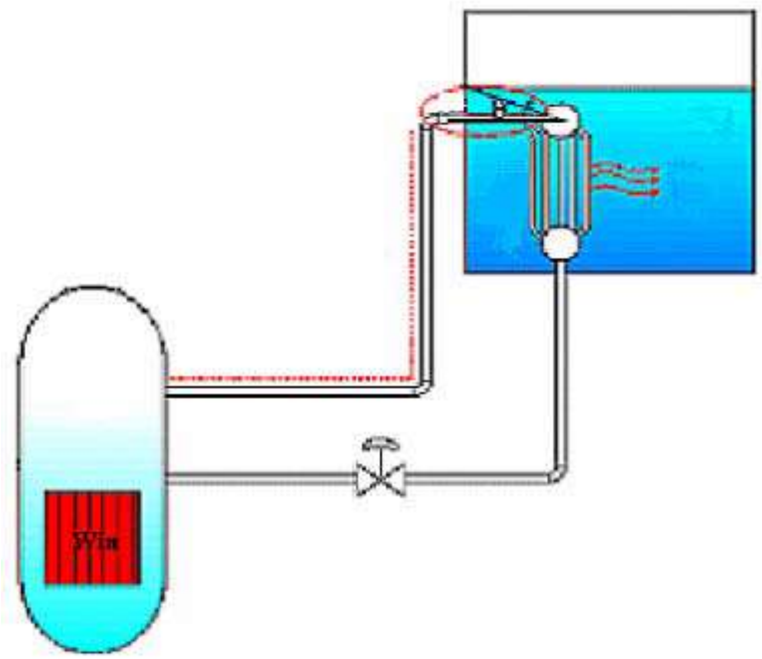

Fig. 1 – Reference passive system for the Technical Opinion Paper (TOP).

3. RELIABILITY (OF A SYSTEM) AND UNCERTAINTY (OF A CALCULATION)

The concepts of reliability and uncertainty are well established in various fields of scientific literature: theory of probability and application of computational tools to solve complex problems constitute example frameworks, respectively. The focus hereafter is the application of those concepts to the evaluation of passive systems:

- An applicable reliability concept may be easily derived considering the pushing of a switch aimed at interrupting the electric current flowing in a wire: if one pushes the switch from its original position (electrical current flowing) 1000 times and he finds that the current does not stop 3 times, he may conclude that the reliability of the system (i.e. the switch) is 99.7%.

- An applicable uncertainty concept needs at least identification of thermal-hydraulic phenomena, computer code development, validation and use in simulating the performance of a system, identification of uncertainty origins and availability of an uncertainty method. The description and/or the understanding of the concept cannot be summarized in a few lines: the reader should consider reference documents, see e.g. [7].

It shall be noted that the application of the reliability concept needs a target mission for the system (i.e. the interruption of the electric current) and an action to compare the target mission with the actual performance of the system. Otherwise, the output of the application of an uncertainty method needs suitable qualification and demonstration of usefulness: e.g. if the predicted uncertainty in calculation output parameters is very large, it is of little use in practical applications and the knowledge of the concerned thermal-hydraulic phenomena may need improvement.

Now, let’s consider the reference system, i.e. the sketch given in Fig. 1: the objective for the activity is to estimate the reliability of the system. At this point we shall introduce the additional constraint that the system is not constructed and no related tests or experiments are available. The following minimum list of steps to perform the activity of evaluating the reliability of the system is needed:

1) To fix a Target Mission (TM) for the system: in this case the target mission is the removal of thermal power keeping the integrity of the core.
2) To consider the envelope of situations, i.e. boundary and initial conditions, in relation to which the system is called into operation.
3) To calculate ‘all’ possible situations, and assigning a Probability to each situation / Mission (PM).
4) To compare calculation results with the target mission.

Two critical issues may be identified at this point in addition to the issue of identifying ‘all’ possible situations:

A) The target mission for the *reliability* evaluation is not as simple as in the case of the switch used to stop the electrical current. Rather the target mission should be connected with thermal-hydraulic phenomena unavoidably implying a transient nature.
B) The calculation of the target mission implies the use of a computational code and the occurrence of *uncertainty*.

The cornerstone achievement at this point can be synthesized as follows:

<we need to calculate the reliability of a thermal-hydraulic phenomenon
whose evaluation is affected by uncertainty>.

Apparently we face with an inherent ambiguity: on the one hand the actual (expected, not known) system performance (then, the *reliability*) is **not affected** by the capability of computational tools (which can be quantified by the uncertainty) adopted for the purpose of analyses; on the other hand, any possible reliability evaluation **is affected** by uncertainty.

In order to solve the ambiguity, already within the first-pioneering proposal of a procedure to evaluate the reliability of a passive system, [8], see also [9], the proposal was made to disconnect uncertainty and reliability: namely, the reliability is the characteristic of a system and the uncertainty is the characteristic of a calculation. Therefore, the reliability is calculated assuming in a first step, that the code is ‘perfect’ (‘zero’ uncertainty) in predicting thermal-hydraulic phenomena expected in the concerned passive system.

3.1 Insights into TH code application

The application of thermal-hydraulic system codes within nuclear reactor safety and design constitutes a broad topic widely discussed in technical literature, see e.g. [10], also needing to address the scaling issue, see e.g. [11]. The following notes supplement and/or justify the assumption of disconnecting the uncertainty evaluation from the reliability evaluation when applying a system thermal-hydraulic code to the analysis of a passive system.

The first note deals with parameter ranges. When looking at parameters ranges expected in the operation of the concerned passive system, i.e. pressure, temperature, steam and liquid velocity, heat transfer coefficient and connected temperature differences, geometry of components including hydraulic diameters, etc., the outcome is that the code is qualified within those parameter ranges including their combinations.

The second note deals with prediction errors. The analysis of experimental data involving passive systems including experiments performed at full scale (pressure, geometry and exchanged power) of IC, show ‘small’ errors (or in-accuracy), or small expected uncertainty bands. The largest contribution to the error is expected to be due to pressure drop coefficient (K_{LOSS}) at geometric discontinuities which may not be considered an inherent code limitation: rather K_{LOSS} values are supplied by code user and may need specific experimental data. The outcome here is that uncertainty in the prediction of passive system performance (excluding the part associated with K_{LOSS}) is negligible (see also next section).

The third note deals with scaling. As a difference from typical phenomena relevant to nuclear reactor safety, large scale or even ‘scale 1’ experiments are available for passive systems. This avoids or reduces the importance of scaling issue. The outcome strengthens the conclusion at the previous note: the uncertainty in the prediction of passive system performance (alone) is negligible.

The fourth note deals with the reliability and the uncertainty in predicting the behavior of the passive system installed within a complex NPP system. Interactions between an assigned passive system and the other regions of a nuclear reactor may reveal a source of instabilities, among the other things; this largely increases error bands of predictions (i.e. the uncertainty) and directly the reliability. The outcome is that even if the reliability of a passive system alone is suitable, a problem (low reliability) may occur when the system becomes a part of a more complex system.

4. TECHNICAL OPINION FOR THE CONCERNED PASSIVE SYSTEM

As an overall result from the previous sections we have that: (a) reliability of a passive system may be reduced to the reliability of thermal-hydraulic phenomena expected during the operation of the system, and (b) reliability can be distinguished and disconnected from uncertainty when analyses are performed.

A not-agreed distinction between uncertainty and reliability by the international scientific community is at the basis of the present paper; the technical opinion makes use of the diagrams in Figs. 2, 3 and 4.

Reliability calculation

The Target Mission (TM) and the Probability of Mission (PM) are envisaged quantities to calculate the reliability of a passive system. Reliability of NC in the reference passive system is of concern here.

The calculation of PM requires the identification of the passive system Boundary and Initial Conditions (BIC) and the consideration of the Origin of Un-Reliability (OUR). Examples of BIC quantities are the pressure, the core power and the distribution of fluid temperature in the system pipelines at the time when the passive system operation is triggered. OUR quantities are discussed in section 4.1. Suitable techniques are needed to evaluate the probability of an initial status for the passive system operation by combining BIC and OUR, see e.g. [12].

The calculation of TM implies the knowledge of the system design conditions: in the concerned case the TM is expected to be a function of the thermal energy removed from the heat source (i.e. core decay heat) during an assigned time period. Several conditions (e.g. mass flow-rate or margin to Departure from Nucleate Boiling [DNBR] greater than assigned values for an assigned time period) may be added to form the TM. The calculation of TM typically needs a thermal-hydraulic computer code as already mentioned.

TM and PM may be related in a diagram as in Fig. 2: each open bullet constitutes the outcome of a calculation which: (a) is performed starting from one PM value and, (b) results in one TM value. A line connecting the open bullets, hereafter called the reliability line, separates reliability and un-reliability regions. Looking at the value PM* one may note that different TM values may be associated to a single PM: the lowest TM value is used to build-up the reliability line. The system reliability may be assumed as connected with the integral of the dotted region above the reliability line: possibly more weight can be given to the TM values close to the region PM = 1.

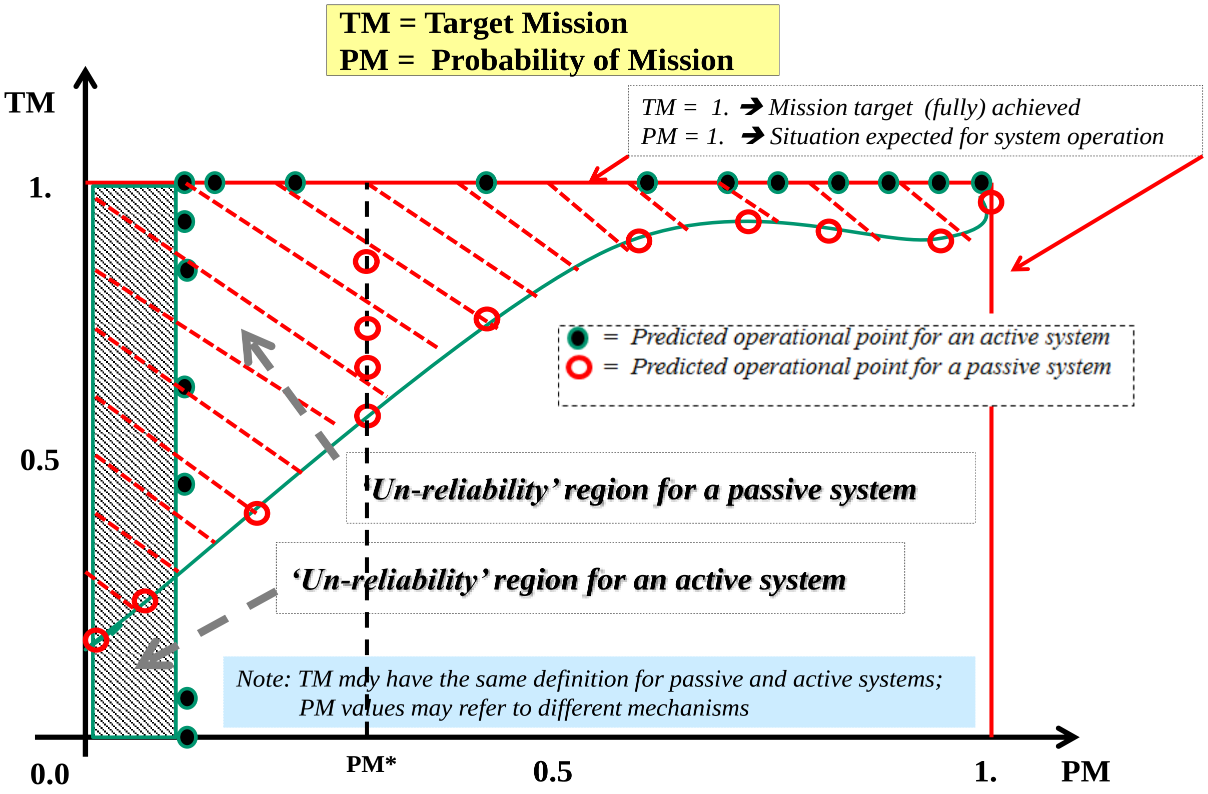

Fig. 2 – Reliability of the reference passive system and comparison with reliability of an active system having the same design mission.

Namely, in the horizontal axis in Fig. 2 (see also Figs. 3 and 4) a continuum of event or states is assumed with their probability integral equal to 1: for instance, in a BWR it is expected that the IC enters in operation when the level of downcomer is within a range A-to-B (where, reasonably, A and B can be 3 and 10 m, respectively); furthermore, the power of core in either BWR or PWR could be in a range 0.5% to 4% of nominal power (e.g. not 30% core nominal power).

Finally, when combining PM and TM, consistent weight can be used if one single measure of reliability is expected (the word 'consistent' implies applicability of the weighting to any comparable system, see also below).

Comparison passive and active systems

TM and PM values, as well as the reliability line have a recognizable relative meaning, although an effort can be made to associate those values and an absolute meaning. Considering the relative meaning, it seems essential to compare the calculated reliability of a passive system with, for instance, the reliability of an active system having the same mission as the concerned passive system. This is done in Fig. 2 and the dense-dotted area on the left (low probability region) is derived. Within nuclear reactor safety, a passive system, other than a lower cost, should show to have a better reliability figure-of-merit than an equivalent active system (a gauss-like probability distribution might be considered for active systems, rather than a line). A variety of situations may occur in practice, other than one passive system substituting an active system, e.g. a) one passive system designed as back-up of an existing active system; b) a reduced quality grade active system used as back-up of a passive system, c) two passive systems used instead of one active system, d) etc. In each case a specific analysis preliminary probabilistic safety type of analysis may be needed before entering into a reliability analysis. Focus is given in the paper to the simplest situation.

Optimization of the design of a passive system

The reliability method, generating TM, PM and the reliability line, may be applied to address questions like the following ones (see the reference system in Fig. 1, and let's call system [A] the system which corresponds to the reliability line derived in Fig. 2):

- Is a new system (system [B]) designed with a higher (or lower) elevation of the pool related to the core better in terms of reliability than system [A]?
- Is a new system (system [B]) characterized by two heat exchangers instead of one better than system [A]?
- Is a new system (system [B]) characterized by larger pipe diameter connecting the RPV and the HEX better than system [A]?
- Etc., including combinations of the above.

The possible answer to (each) one of the questions can be found in Fig. 3: system [B] appears better than system [A] if no high weighting of high probability region is adopted; otherwise (high probability region highly weighted) system [A] appears better.

Role of overall system modeling and of uncertainty in the prediction

The reliability and the uncertainty in predicting the performance of a passive system alone may be different when the performance of an overall nuclear reactor system (the NPP) equipped with a passive system is dealt with. Key situations are depicted in Fig. 4 where expected impact of uncertainty upon reliability prediction is visualized:

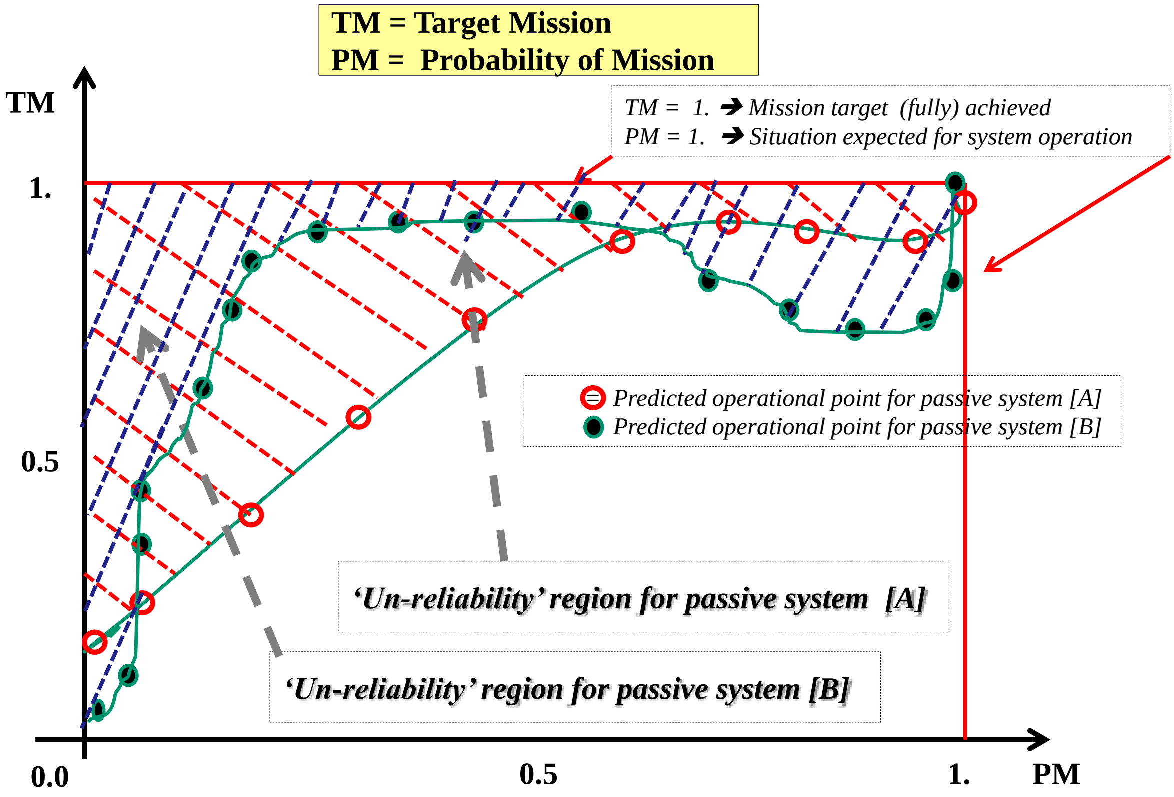

Fig. 3 – Reliability of the reference passive system and comparison with reliability of a modified version of the same system.

- The uncertainty in predicting reliability relevant scenarios for the system sketched in Fig. 1, passive system alone, moves the reliability line from curve "1" to curve "2" (thin black arrows in Fig. 4): vertical arrows represent (small expected) errors associated with the evaluation of TM by a system thermal-hydraulics code and horizontal arrows are associated with errors in estimating PM.
- The outcome of reliability analysis of the passive system embedded into the overall reactor system (or the NPP, i.e. with all systems reacting; in other terms the same analysis performed for the passive system alone is now repeated with all other systems modeled), may reveal different from curve "1": reliability line "3" may result.
- The uncertainty in predicting reliability relevant scenarios for an overall NPP which includes the system sketched in Fig. 1 moves the reliability line from "1" to "4" in Fig. 4: vertical arrows represent (large expected) errors associated with the evaluation of TM by a system thermal-hydraulics code; in this case the same horizontal arrows are associated with errors in estimating PM (not shown in the diagram).

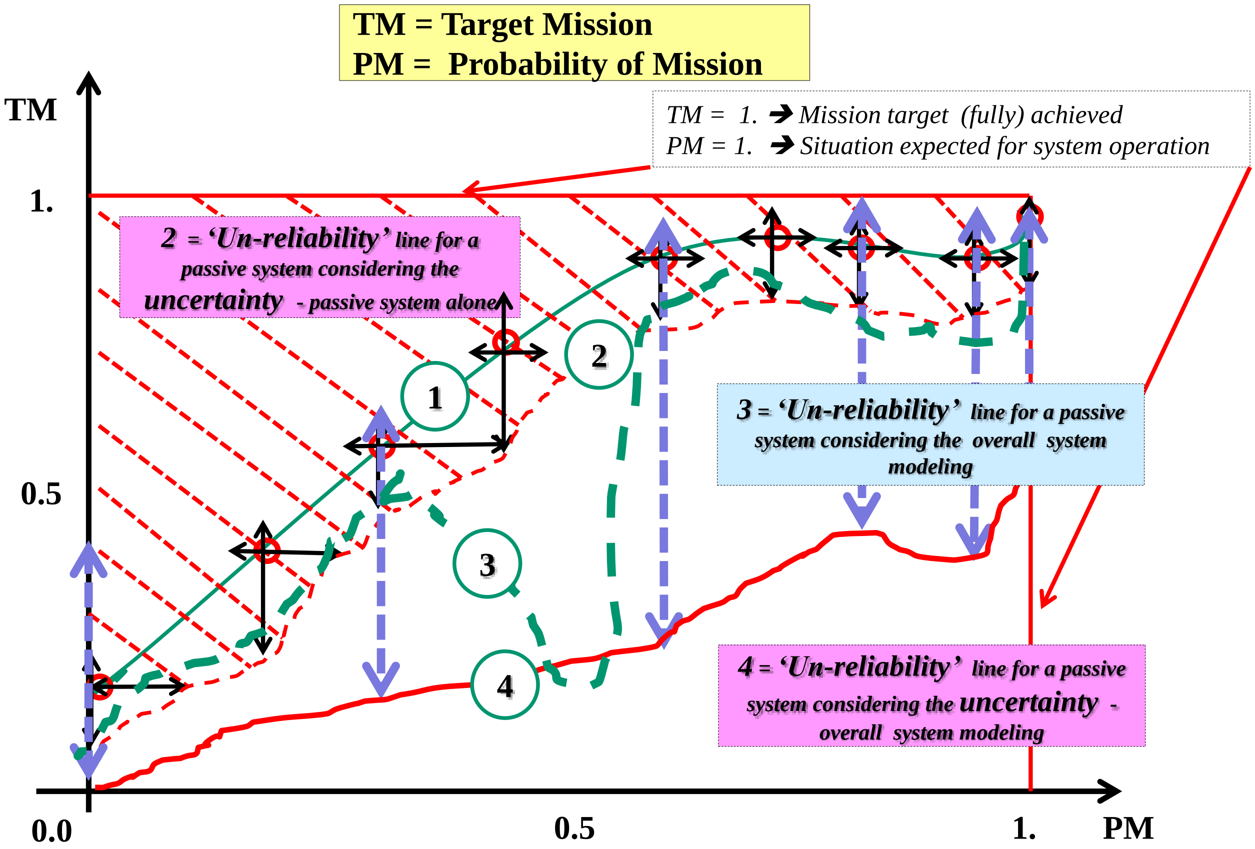

Fig. 4 – Reliability of the reference passive system and impacts of uncertainty of code prediction considering the passive system alone and the passive system interacting with other systems in the plant [line "1" is the reliability line expected for the passive system alone, see Fig. 2] .

Making reference to Fig. 4, it shall be noted that reliability line "1" is the outcome of a reliability calculation where the adopted computational tool is assumed to be without errors (or 'perfect'). The line "1" is expected in case a large number of scale-1 experiments are performed.

Furthermore, the lines "2" to "4" need the application of computational tools. Namely, the line "2" is expected to be close to the line "1" because of suitable validation of current computational tools. The lines "3" and "4" imply modeling of the overall system (the NPP): line "3" is the outcome of the analysis when reliability origins (passive system alone embedded into the overall system) are considered and line "4" is the outcome of the analysis when uncertainty origins (related to the overall system) are considered.

4.1 Origins of uncertainty and un-reliability

The origins of uncertainty in thermal-hydraulic code predictions were proposed early in 1998, [13], and later on spread in various papers and documents, see e.g. [14]. Namely, the origins of uncertainty are connected with imperfect modeling (also called epistemic) and imperfect knowledge of boundary conditions (also called aleatory); the latter group providing lower contribution to the overall uncertainty. Methods to evaluate the uncertainty are discussed in available literature, see also [7].

The reasons or the origins of un-reliability for passive system can be found in papers discussing the reliability of passive systems, see e.g. [2], [8], [9], [12], [15] and [16]. Here we shall confirm that the origin of un-reliability shall be connected with the design and the operation characteristics of the (passive) systems. As a key difference from the origins of uncertainty, no epistemic or aleatory type of unknowns is distinguished; rather, parameter ranges which characterize the design of the (passive) systems are involved. Table I has been built In order to clarify the differences between uncertainty and reliability quantities, by providing examples of parameters belonging to each of the three classes (columns 3 to 5 starting from left) 'reliability of passive system design', 'uncertainty of thermal-hydraulic phenomena expected in the operation of the passive system alone' and 'uncertainty of thermal-hydraulic phenomena expected in the operation of the passive system embedded into the nuclear reactor (or the NPP)'. The table makes reference to the system in Fig. 1 and to the expected results from reliability and uncertainty studies given in Figs. 2 to 4.

Table I – List of quantities affecting reliability and uncertainty analysis of the reference passive system in Fig. 1.

No	**QUANTITY IDENTIFICATION**	**UNCERTAINTY**		**RELIABILITY** Passive System Design (°°)	**NOTES**
		Passive System (°)	NPP with Passive System(°)		
1	Pressure		X		Aleatory, e.g. nominal +/- 0.8%
2	Pressure			X	Range*, e.g. 1 – 10 MPa
3	Core power		X		Aleatory, e.g. nominal +/- 10%
4	Core power			X	Range*, e.g. [0.1-4]% core power
5	HEX heat transfer coefficient	X			Epistemic, negligible impact
6	Heat losses IC piping			X	Range*
7	Countercurrent flow in core		X		Epistemic, if occurring
8	Two phase critical flow		X		Epistemic, if occurring
9	K_{LOSS} various locations of IC	X			Epistemic
10	K_{LOSS} various locations of NPP		X		Epistemic
11	Partial closure of isolation valve			X	Not shown in Fig. 1; range*
12	Partial opening of IC valve			X	Shown in Fig. 1; range*
13	Horizontal pipe inclination			X	Range*; irrelevant for active systems
14	Non condensable gas in IC pipe			X	
15	Elevation of IC pool			X	Alternative passive system design optimization, see Fig. 3.
16	No of HEX in the pool				
17	Diameter of IC piping				

(°)Relevant to Fig. 4; (°°) Relevant to Figs. 2 and 3; *to be specified by IC designer; expected for operation of the passive system; range split in several regions; each region of the range may correspond to a probability

4.2 Attributes of a reliability study

A comprehensive reliability study supported by uncertainty analysis is expected to provide methodological approaches:

- to identify a full list of parameters distinguishing into three categories as given in Table I (see section 4.1);
- to characterize the range of variations of parameters (see e.g. [8]);

- ⇨ to identify and to characterize the Target of Mission and the Probability of Mission (TM and PM as introduced in Fig. 2), see e.g. [12];
- ⇨ to derive the reliability lines (e.g. as defined in Figs. 2, 3 and 4) and to identify (as far as possible) objective values for the system reliability which can compare with the reliability of components of equivalent active systems;
- ⇨ to allow the comparison between a passive system and an active system having the same Target of Mission, see also Fig. 2;
- ⇨ to allow the optimization of the design of a passive system, see also Fig. 3;
- ⇨ to perform supporting uncertainty studies (as introduced in Fig. 4), see e.g. [7].

Results from the reliability study may include diagrams as those in Figs. 2 to 4.

5. CONCLUSIVE REMARKS

The present Technical Opinion Paper aimed at finding a common understanding among currently debated topics dealing with reliability and uncertainty of passive systems. In order to facilitate the objective the analysis is focused to one specific system, a NC based system for passive removal of core power in either BWR or PWR.

Three areas for conclusive remarks are identified below.

A) The Natural Circulation. NC implies the use of gravity force for transferring thermal power from an assigned heat source to an assigned heat sink. The driving forces depend upon differences in fluid density between a rising side, referred as chimney, and a descending side, referred as downcomer. When water is used as acting fluid assuming typical (design detail) elevation differences between source and sink, driving head expressed in *meters of liquid water at ambient pressure and temperature* is of the order of 10^{-1} and 10^{0}, when single-phase and two-phase conditions are concerned in the system design, respectively. Those values should be compared with values of the same quantity in the range $10^{1}\div10^{2}$ when (typically centrifugal) pumps are installed in similar loops, called forced circulation (FC) loops, designed to transfer the same thermal power from the source to the sink. Noticeably, same thermal power is transferred by NC and FC loops with differences in driving forces for two or three orders of magnitude.

It seems essential that the capabilities of a passive system are compared with the capabilities of an equivalent active system having the same design target.

B) The distinction between reliability (of a system) and uncertainty (of a calculation). The concepts of reliability and uncertainty and the related methods are basically different. First, reliability shall be related to a system including its operational conditions, otherwise uncertainty is the attribute of a calculation. Second, uncertainty analysis may reveal a key support to an uncertainty study. Namely, the introduction of one or more passive systems in any NPP creates new possibilities for the evolution of transient scenarios, adding new uncertainties to the evaluation of the overall scenarios in the presence of passive systems.

It is proposed to perform uncertainty analysis at two levels following a reliability study. The former is concerned with the passive system alone and may not bring to substantial changes in the reliability figure. The latter is concerned with the entire NPP and may dramatically decrease the reliability of the passive system.

C) The attributes of a reliability study. Suitable methodologies are needed and should be connected to perform a reliability analysis. Design conditions for a passive system should be identified first. Target of Mission and Probability of Mission should be defined and shall constitute the objective of calculations. The envelope of calculation results may constitute a reliability line and a measure of the objective reliability of the concerned passive system. Reliability of a passive system alone may be different from reliability of the same system (with the same mission) as part of a complex system (e.g. the nuclear reactor). Uncertainty analysis is needed to support reliability evaluation.

The key conclusions are:

- a reliability analysis may reveal necessary to demonstrate the effectiveness of a passive system and to optimize its design;

- reliability studies supported by uncertainty evaluation may show that passive systems alone are not protecting the core of nuclear reactors in each foreseeable accident condition; furthermore, based on a successful reliability analysis, the suitability of an optimized passive system added to an existing set of active systems may be justified;

- as a side consequence of the reliability study, e.g. the identification of reliability parameters, specific licensing rules are needed for approving the operation of passive systems;

- the reliability of operation of a passive system, once a target mission is assigned, may reveal not unitary;

- justification of large power nuclear reactors (NPP) protected only by passive systems may require large efforts and resources.

The outcomes of the paper or, better, the results of reliability analyses possibly based on the considerations in the paper, are applicable to any passive system, noticeably including SMR and AP-1000. However, results shall focus upon individual systems in relation to which design details are known and reliability analysis is performed. This is not the case of either AP-1000 or any SMR: therefore no conclusion can be drawn in relation to those systems.

Furthermore, the impact upon safety evaluation and licensing of any reliability study should distinguish the situation where a passive system is used as a substitute of an active system from the situation where a passive system is used to attribute a diverse redundancy to an active system. In the latter case, i.e. combination active and passive system, a reliability study may be performed to optimize the overall system, eventually proving that this is the optimal solution.

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